# Milky Way, Interstellar Medium and Nearby Galaxies Sub-group

Cara Battersby & Karin Sandstrom

# Our Scope

- Star formation and interstellar medium in the Milky Way down to the scales of protostellar objects
- The Local Group
- Galaxies that we are able to resolve (i.e. not point sources for a Far-IR Surveyor)

# Working Group

- Members of the STDT:
  - Susanne Aalto, Maryvonne Gerin, David Leisawitz, Margaret Meixner, Gary Melnick, Stephanie Milam, Desika Narayanan, Deborah Padgett, Klaus Pontoppidan, Thomas Roellig
- Community Involvement:
  - Low Mass Star Formation
    - Per Bjerkeli, Mike Dunham, Will Fischer, Chat Hull, Leslie Looney, Karin Oberg, Sarah Sadavoy
  - High Mass Star Formation
    - James Aguirre, John Bally, Neal Evans, Roberta Paladini, Thushara Pillai, Steve Longmore, Jill Rathborne
  - Milky Way ISM  & Galactic Structure
    - Tom Dame, Paul Goldsmith, Mark Heyer, Nia Imara, Jorge Pineda, Julia Roman-Duval,
  - Nearby Galaxies
    - Angela Adamo, Alberto Bolatto, Julia Kamenetzky, Adam Leroy, Dimitra Rigopoulou, Erik Rosolowsky, Marta Sewilo, JD Smith

# Our Process so far

- Invited community members to participate in the working group
  - Excellent response!
  - More participation than we anticipated.
- Started with a broad brainstorm of key science questions.
  - Participation by ~20 people in the sub-group
- Telecon on May 2 to discuss the initial science question list
- Consolidation, refinement of list based on sub-group feedback
- From May 2 till now, work on next iteration of the list
  - Feedback via wiki page - excellent participation so far!
  - People sign their name on top 5 goals, provide feedback on the types of observations that could address these questions, how uniquely suited to the Far-IR Surveyor the question is, provide key references and plots on the subject.
- A lot of work yet to be done to finalize and prioritize the list

# The Big Picture

Cosmology, Large Scale structure

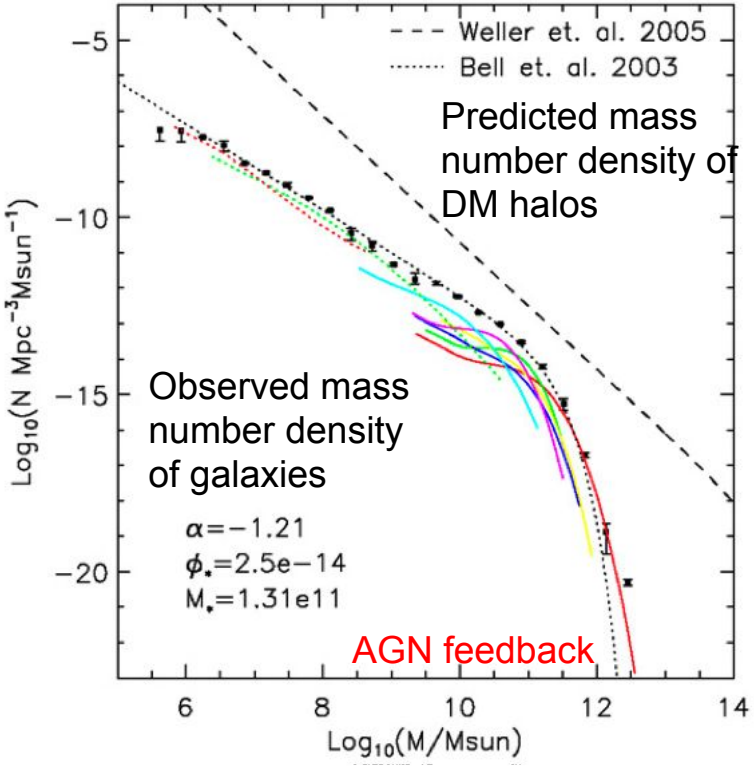
Galaxy evolution

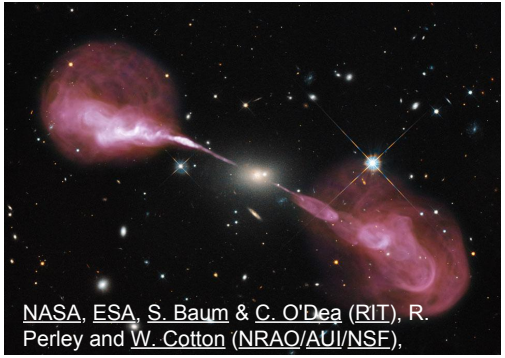
**Our group - MW/Local Galaxies**

Formation of planets & life

# Connecting between cosmology and galaxy evolution to planet-forming disks


SN feedback



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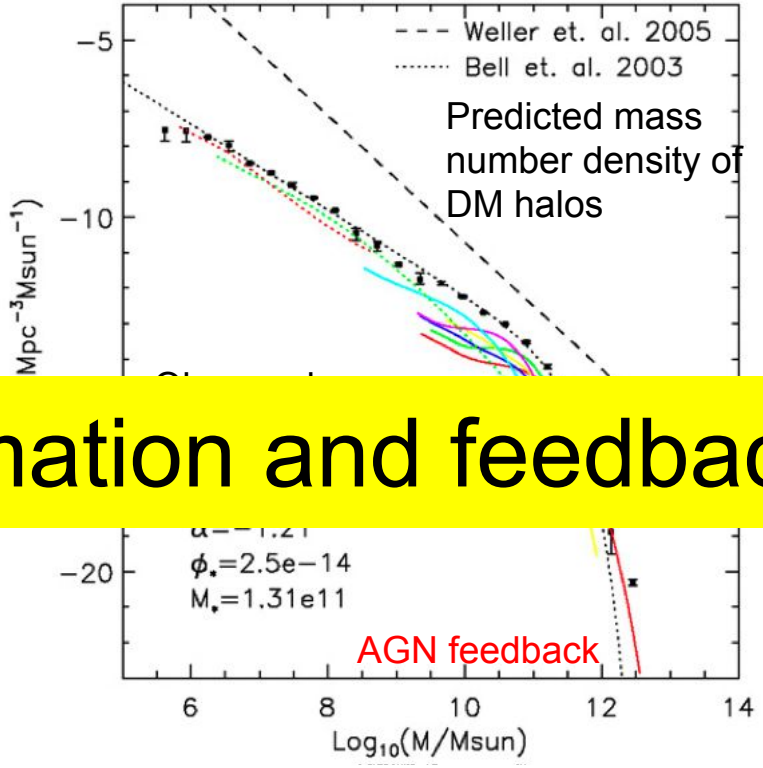
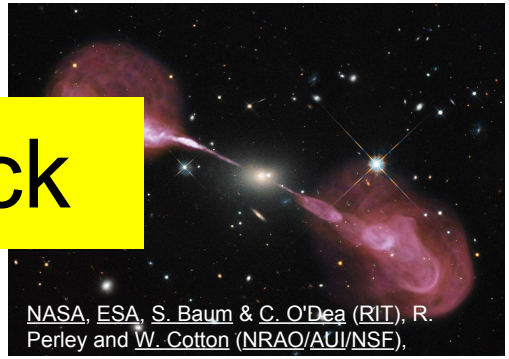
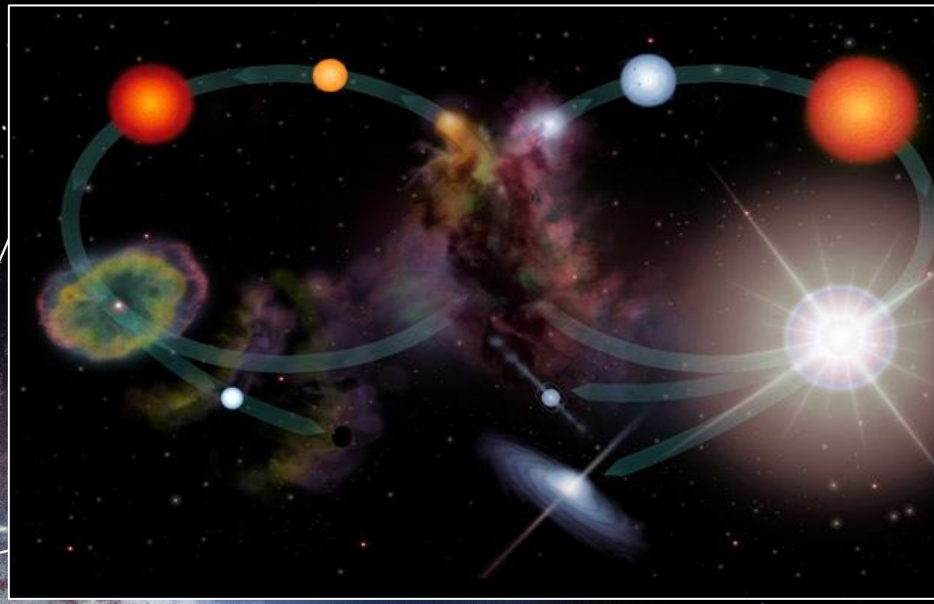



## Star formation and feedback



How are star formation and feedback regulated in galaxies and how do they interact with the wider environment?



Credits: ESA/ATG Medialab

What is the interplay between SMBH feeding and star formation?

How do star formation and feedback processes vary with environment?

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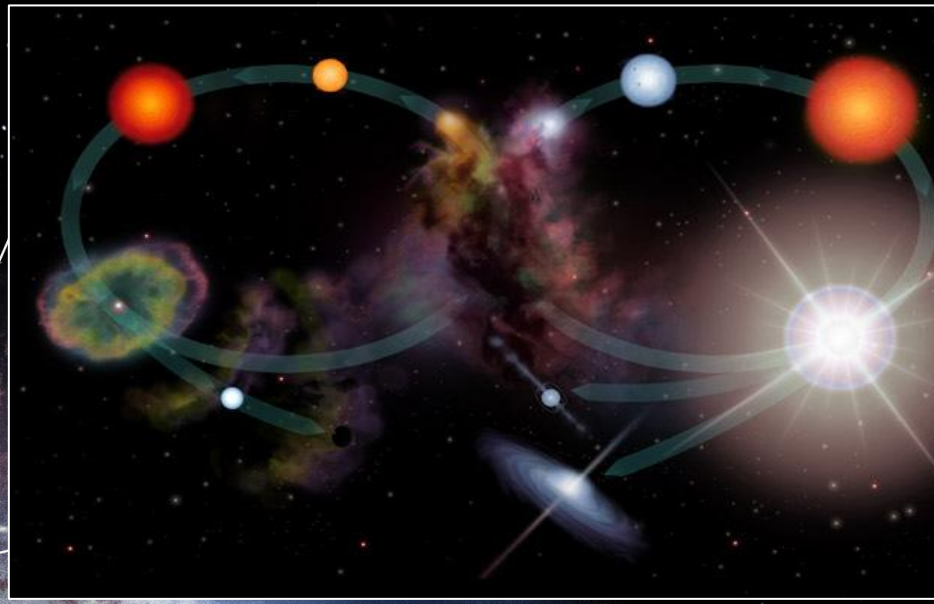

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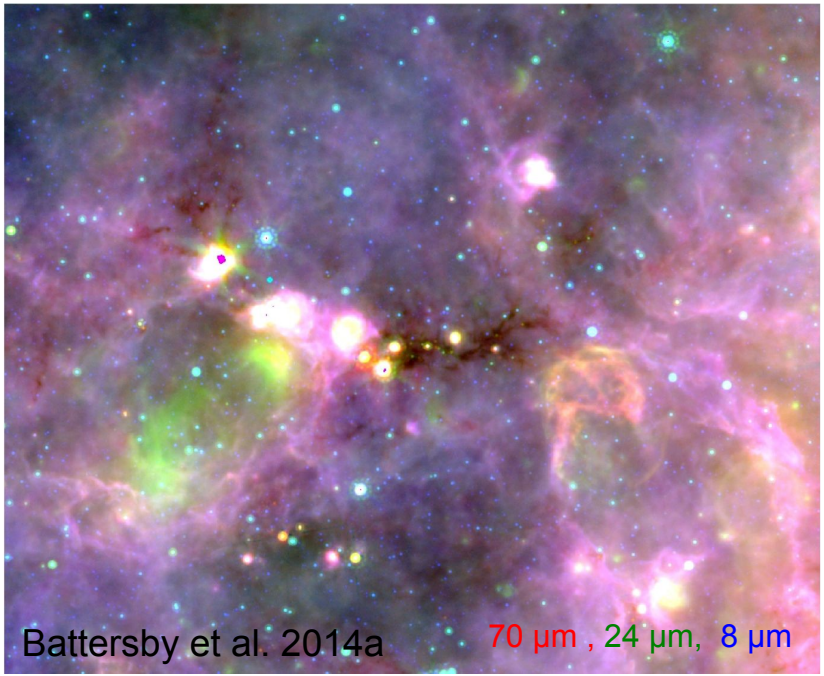


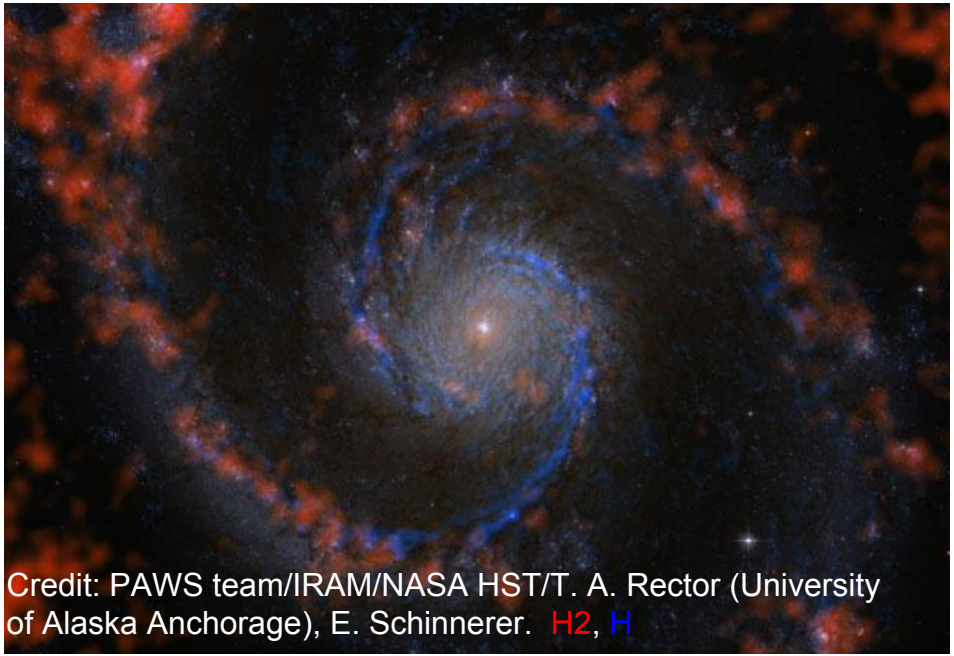

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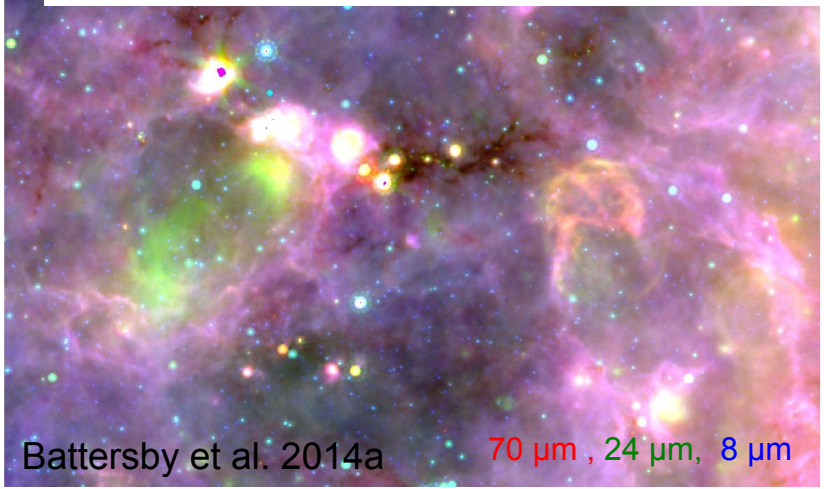
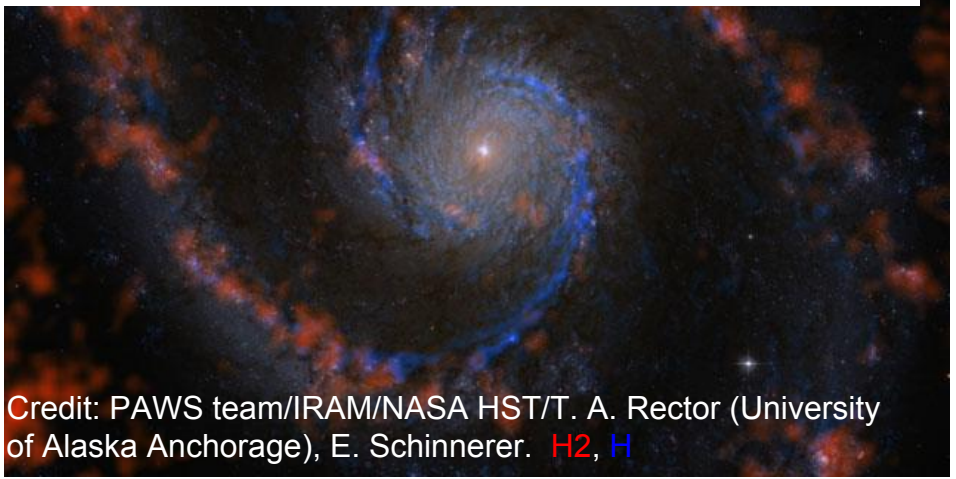
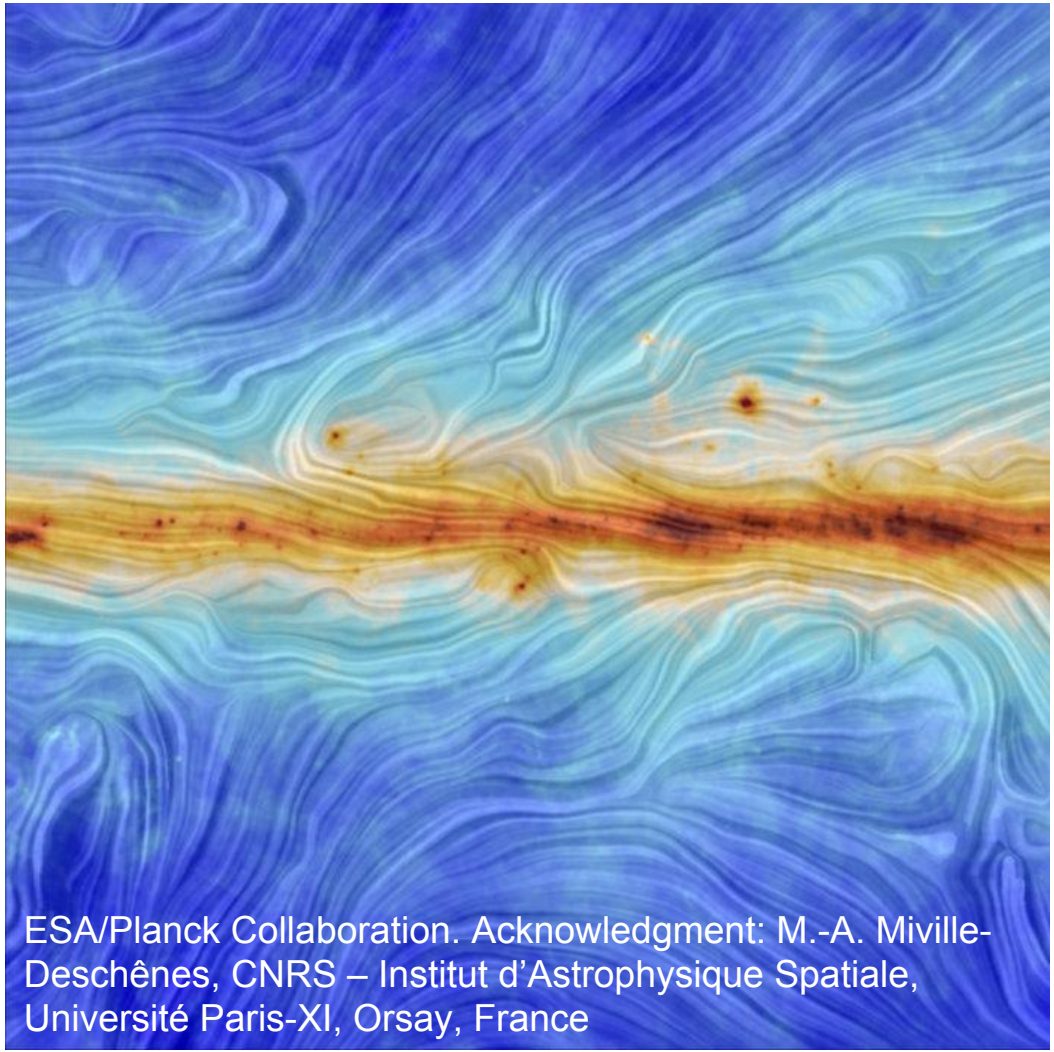
→ Resolved molecular cloud observations in nearby galaxies showing varying levels of spiral arm structure (and metallicity, surface density, star formation rate, etc.) – *very high spatial resolution sensitive observations*.

→ Resolved *kinematic observations of C+ / C / CO* in our Galaxy and nearby galaxies (transition from atomic to molecular).



What is the **magnetic field** structure of our Galaxy from kpc to protostellar core scales? What regulates the coupling of matter with magnetic fields and what is the role of magnetic fields in star formation?



ESA/Planck Collaboration. Acknowledgment: M.-A. Miville-Deschênes, CNRS – Institut d'Astrophysique Spatiale, Université Paris-XI, Orsay, France

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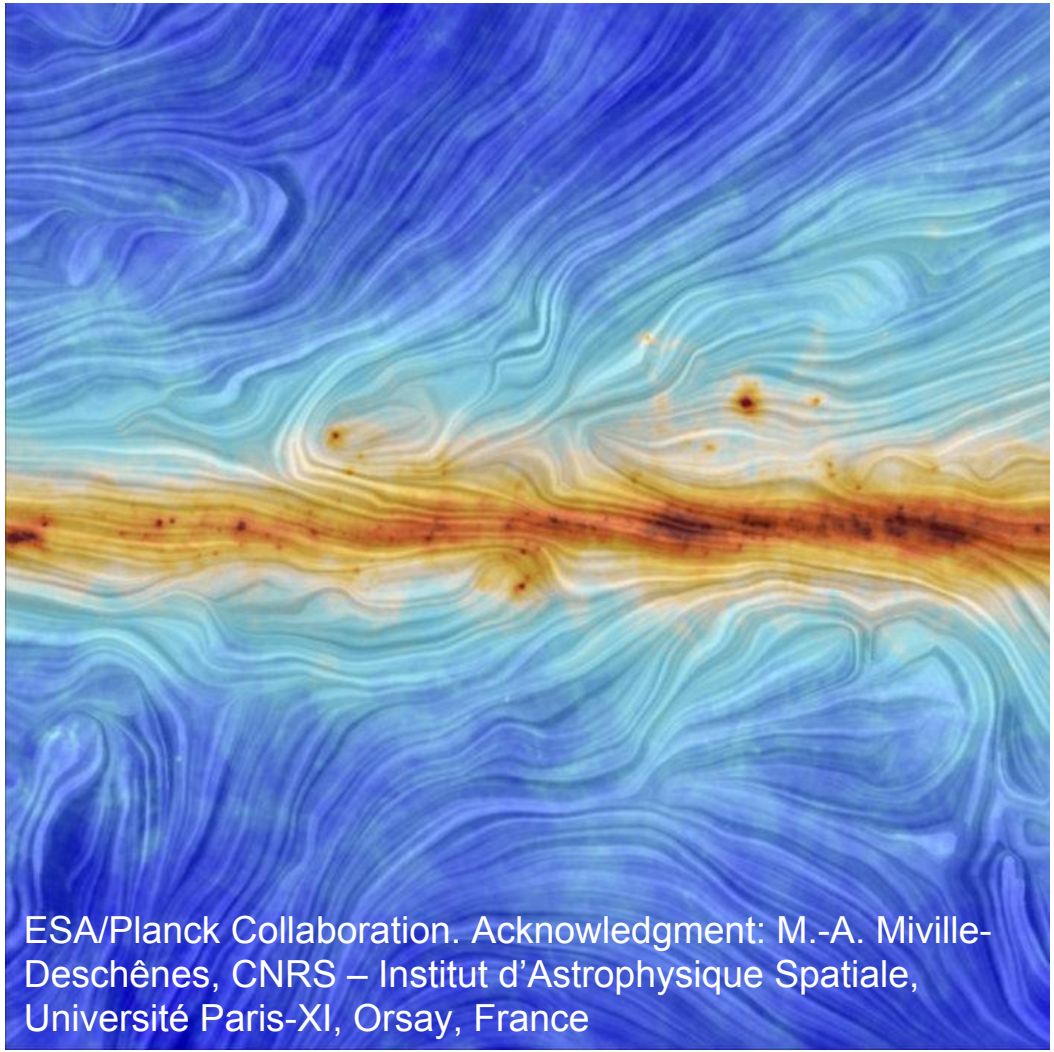
→ FIR is near peak of dust emission. Wide-field mapping, combined with high-resolution, will allow for major new discoveries. *Wide-field, high-resolution dust continuum polarization.*



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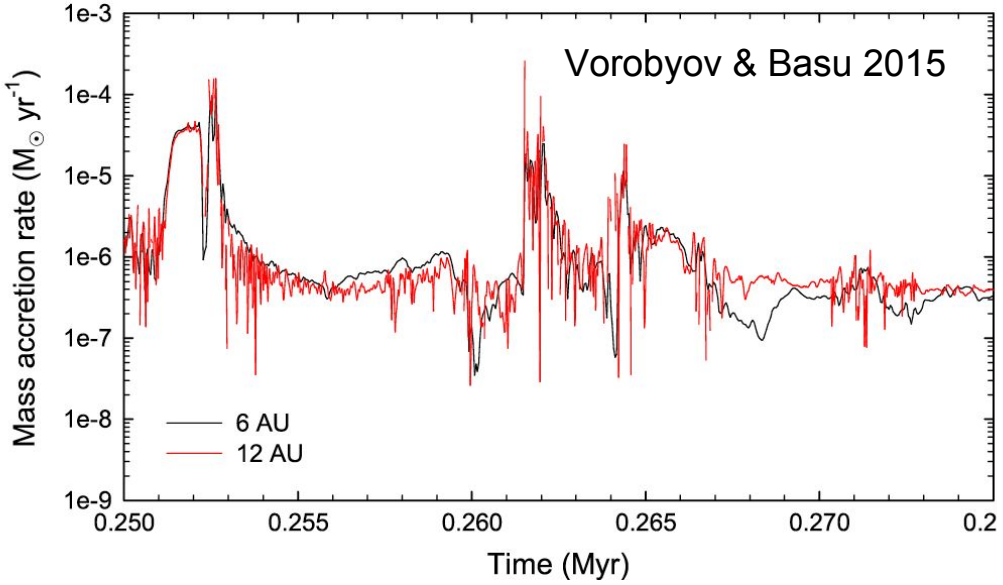
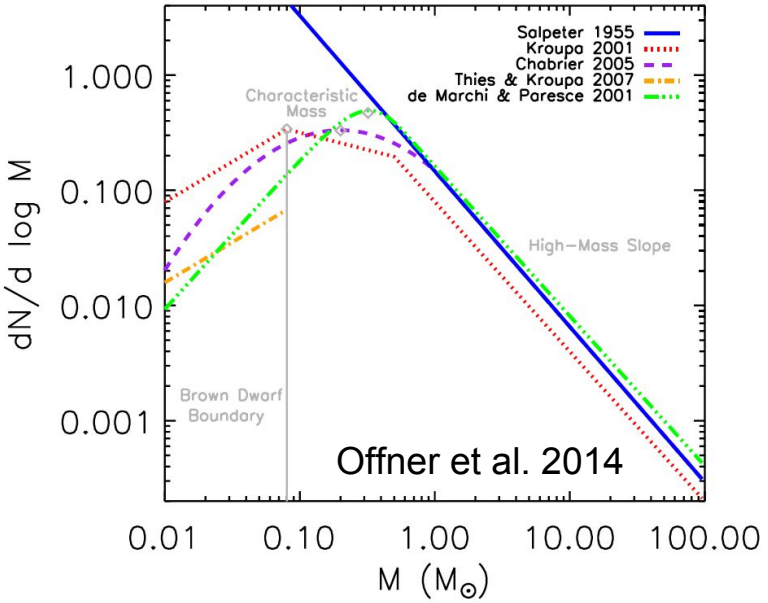
What are the physics responsible for the universality of the **IMF**? What is the origin of of stellar multiplicity, i.e. what regulates the **fragmentation process**? What determines the Core Mass Function and can it be mapped onto the IMF? How is **mass accreted** onto stars and what is the role of major/minor accretion events?



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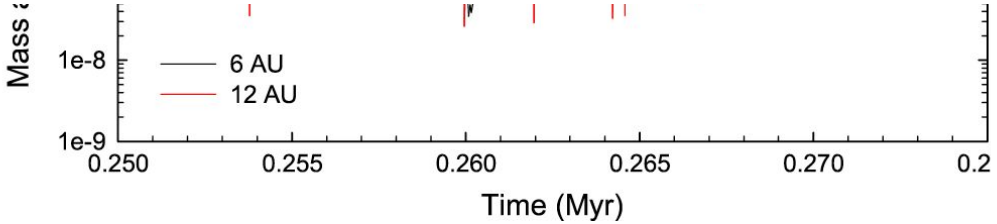
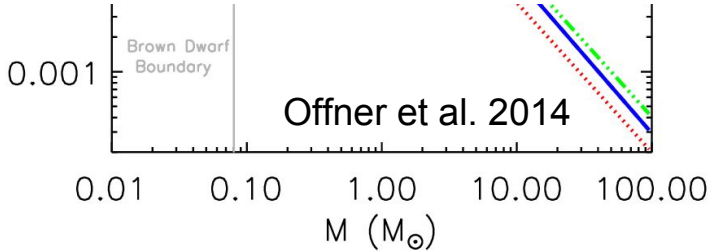
→ Measure the Core Mass Function with great precision (spatial and spectral resolution) in a variety of environments (Galactic disk, Galactic Center, Galactic "starburst" clusters like W51 or SgrB2, LMC and lower-metallicity SMC). *Very high spatial and spectral resolution in dust continuum and molecular lines, over several key regions.*

→ Flux monitoring of the dust continuum of young stars with high cadence and/or proper motion measurements of molecular gas near young stars - *requires very high spatial resolution. Ideally done where protostar SEDS peak in the Far-IR*



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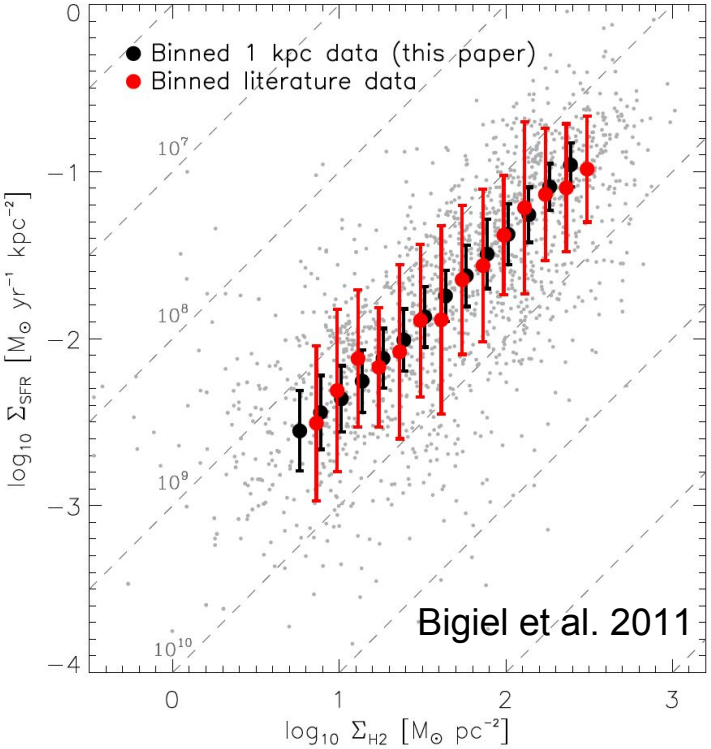


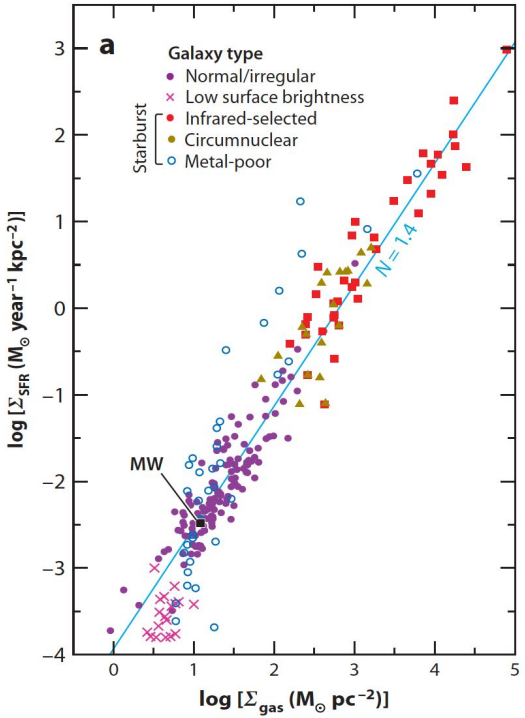


Kennicutt & Evans 2012, adapted from Gao & Solomon 2004

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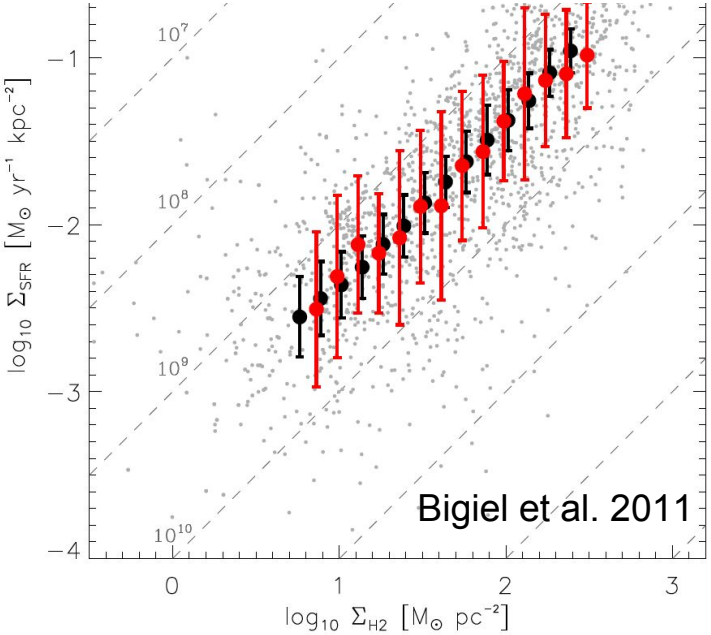
→ resolved star formation in a variety of environments (nearby galaxies). *High spatial resolution spectral line and dust observations.*

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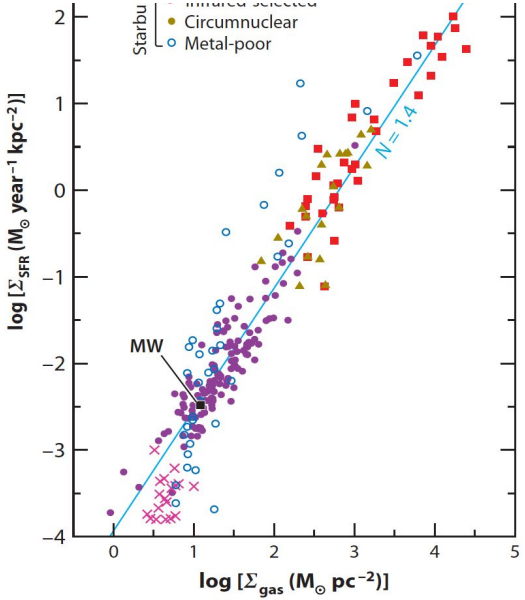
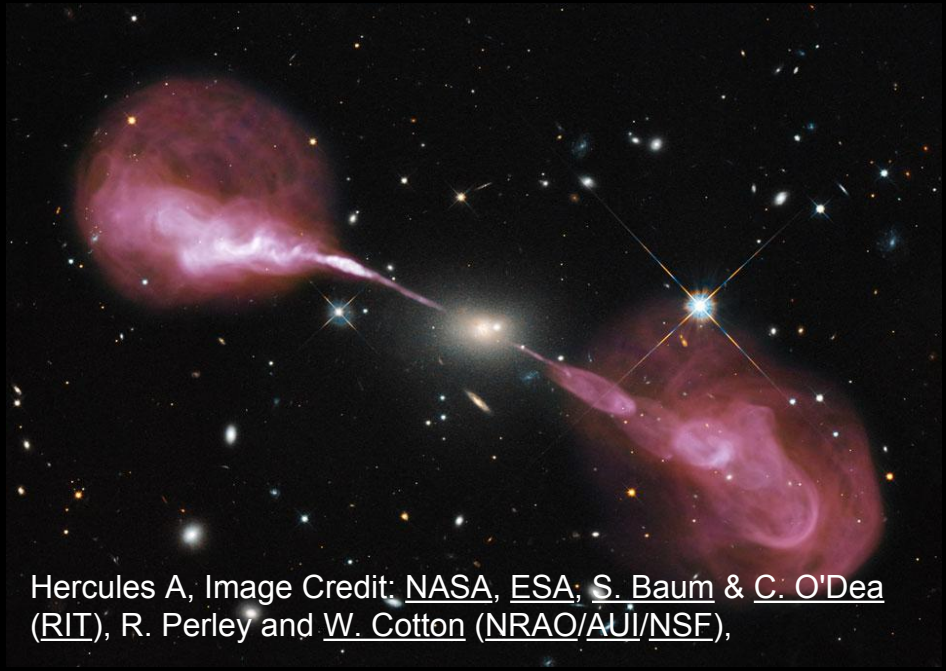
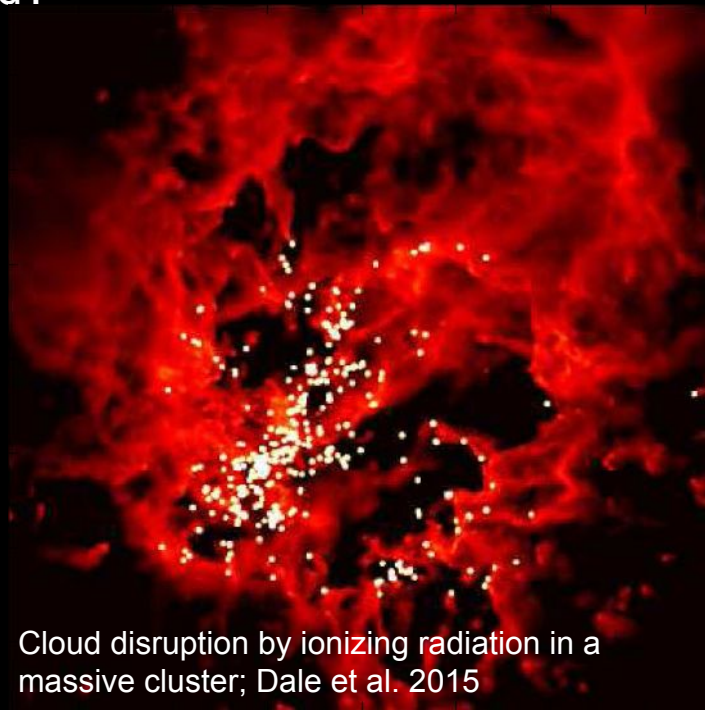


How does **feedback** from star formation and AGN impact the ISM and IGM? Where and how does ISM **turbulence** decay? What are the generation and injection scales and sources? What is the census of material recycled/expelled from galaxies and how does it affect the **circumgalactic environment**? How is material expelled from galaxies? How is it (re)accreted?



Hercules A, Image Credit: NASA, ESA, S. Baum & C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF),



Cloud disruption by ionizing radiation in a massive cluster; Dale et al. 2015

How does **feedback** from star formation and AGN impact the ISM and IGM?

→ High-J CO line emission, PDR lines (CII, OIII, OI, etc.). *High-J CO lines*

Where and how does ISM **turbulence** decay?

→ wide-field mapping of high-J CO lines. *High-J CO lines, wide-field*

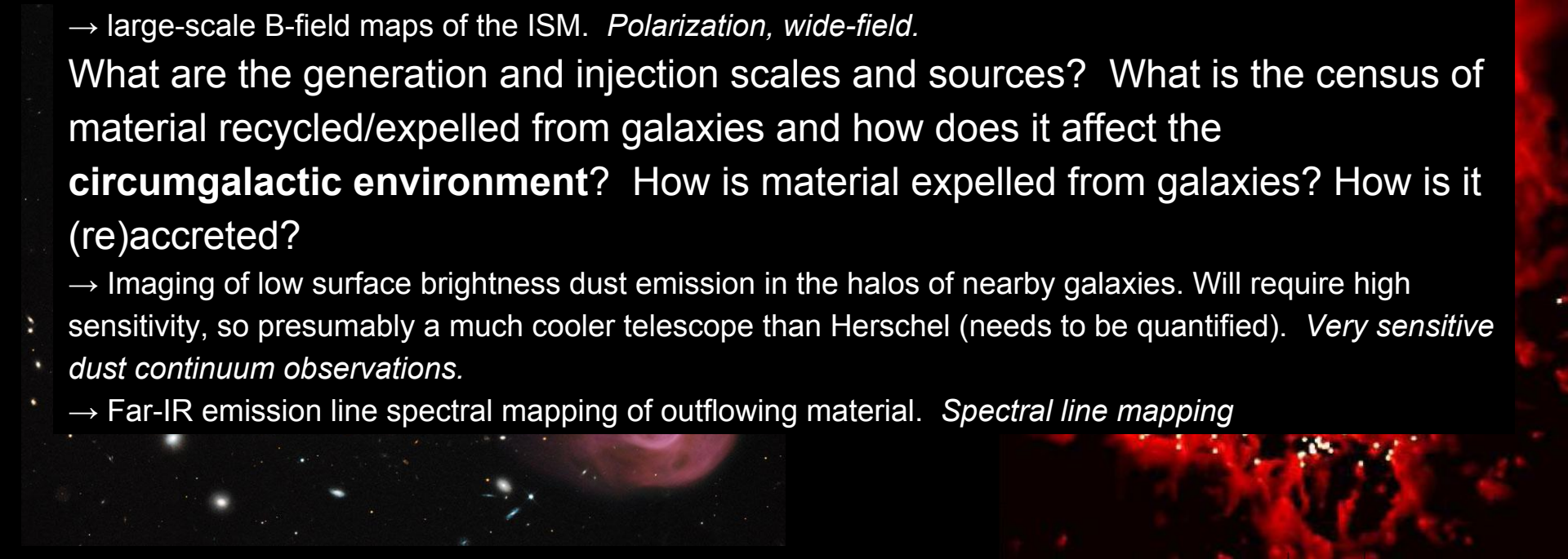
→ Proper motions of shocks across clouds through resolved spectroscopy. *Very high spatial resolution in spectral lines.*

→ large-scale B-field maps of the ISM. *Polarization, wide-field.*

What are the generation and injection scales and sources? What is the census of material recycled/expelled from galaxies and how does it affect the **circumgalactic environment**? How is material expelled from galaxies? How is it (re)accreted?

→ Imaging of low surface brightness dust emission in the halos of nearby galaxies. Will require high sensitivity, so presumably a much cooler telescope than Herschel (needs to be quantified). *Very sensitive dust continuum observations.*

→ Far-IR emission line spectral mapping of outflowing material. *Spectral line mapping*



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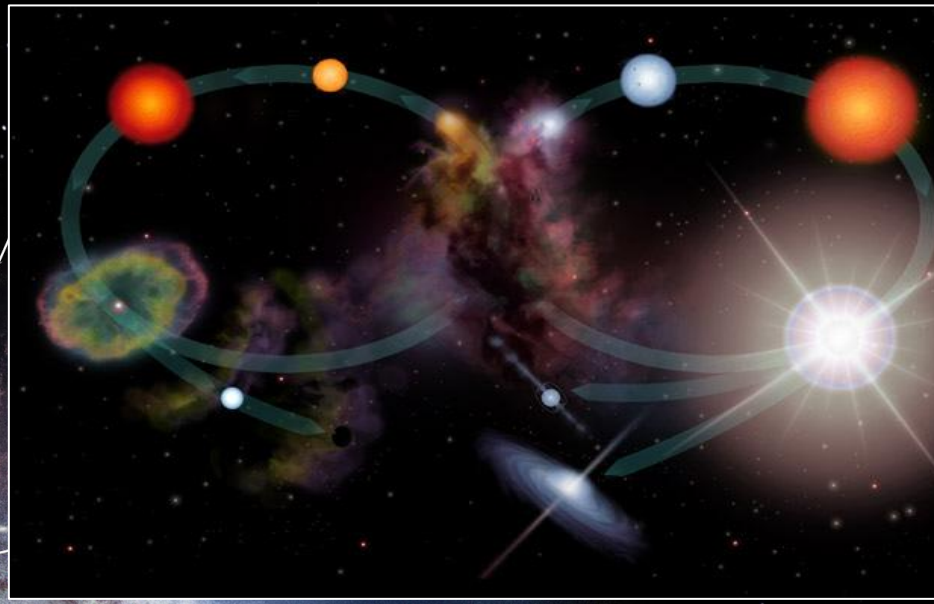
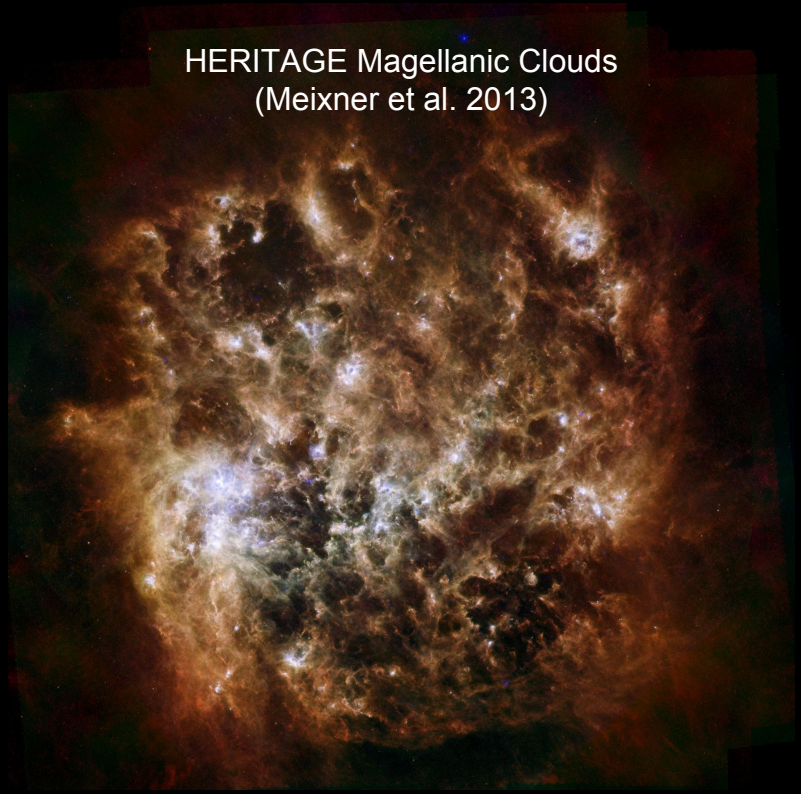


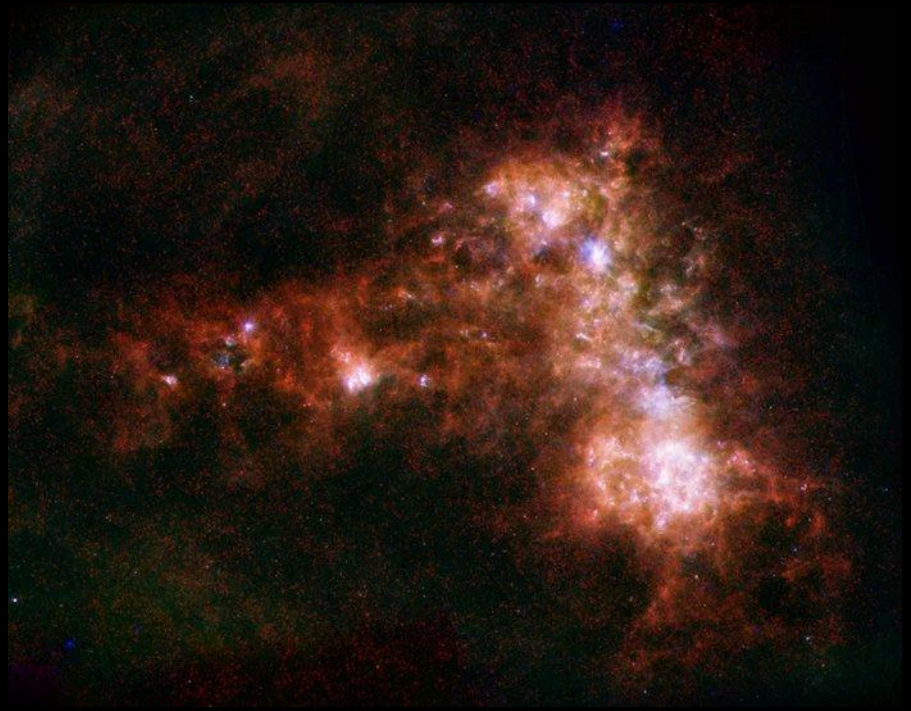
Credits: ESA/ATG Medialab

What is the interplay between SMBH feeding and star formation?

How do star formation and feedback processes vary with environment?

How do the star formation efficiency, molecular depletion times, and relative importance of feedback mechanisms depend on metallicity, turbulence, density, surface density, and other **environmental factors**?



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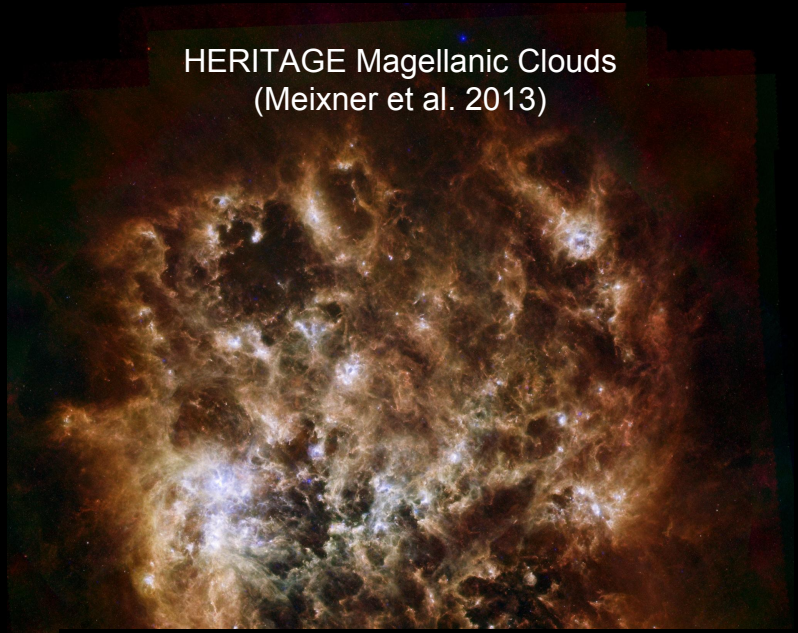


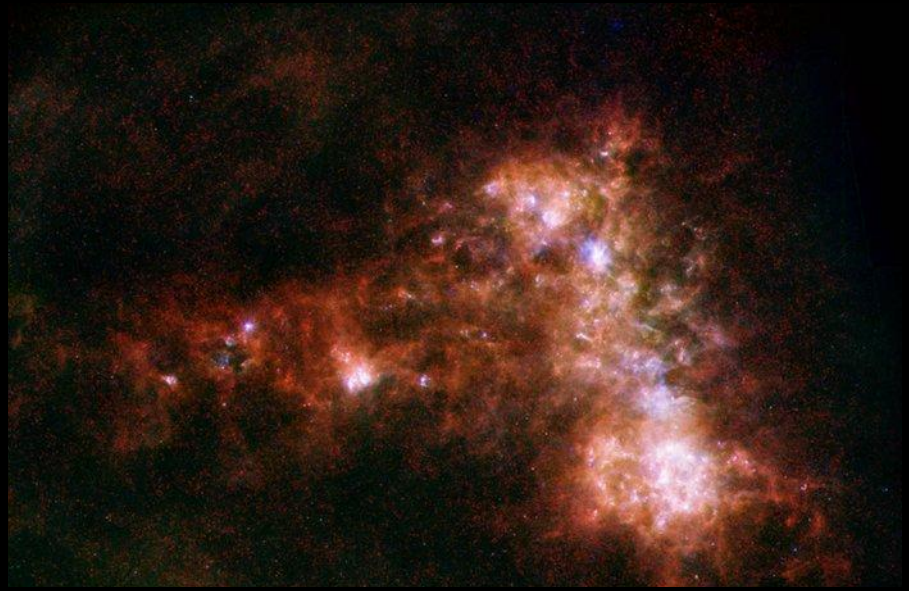

→ Local Group molecular cloud scale observations of gas & dust

→ Far-IR, sub-mm line mapping (high-J CO, [CII], [CI], etc)

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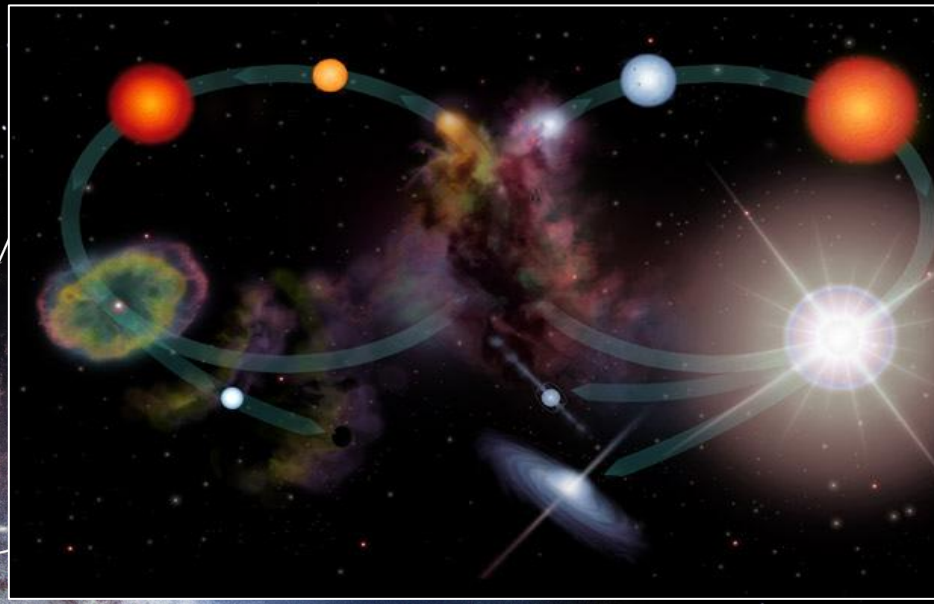

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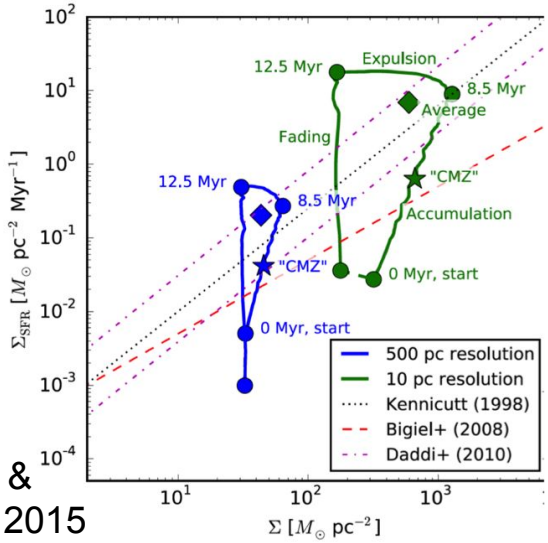
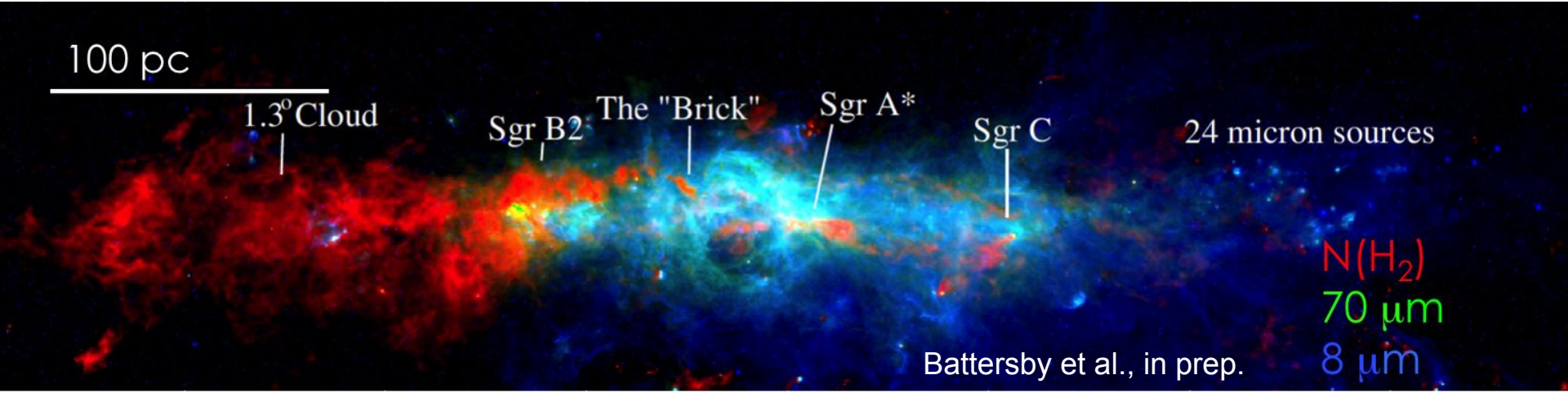



Krumholz & Kruijssen 2015




Battersby et al., in prep.

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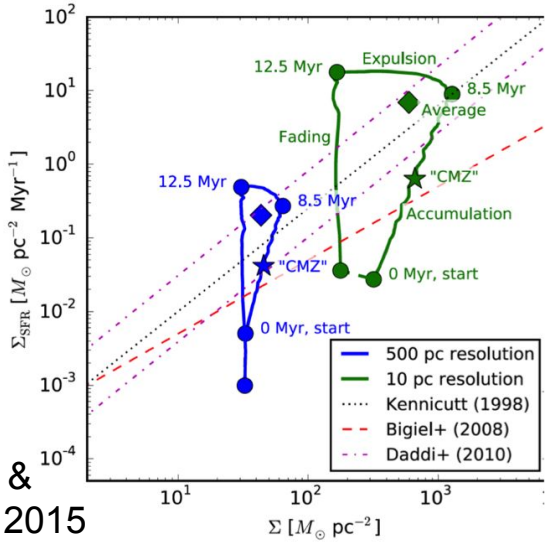
→ Resolved accretion onto SgrA* in our Galaxy

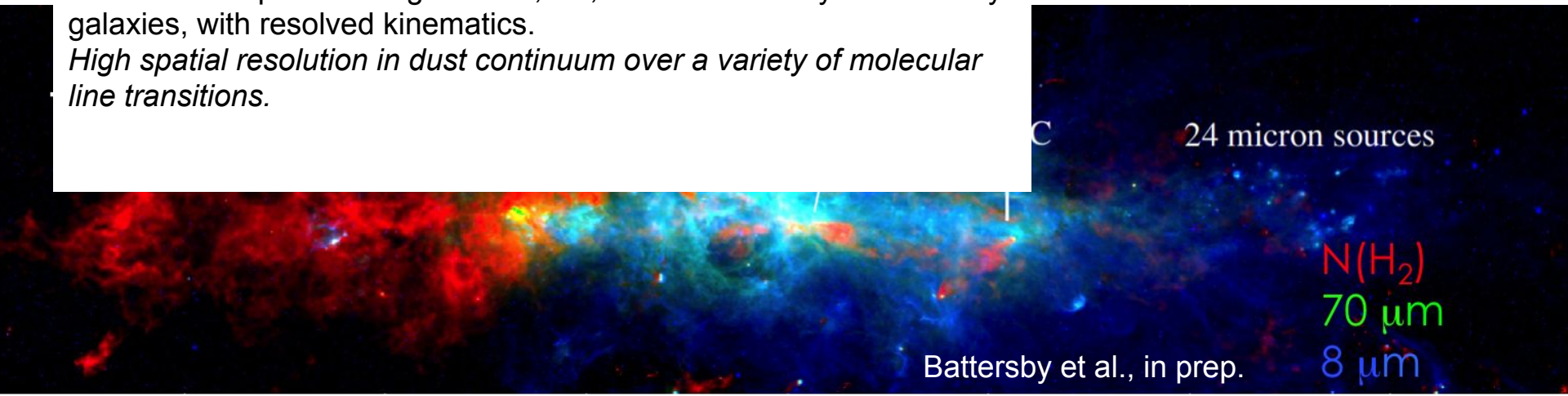
→ Large overview of gas flows and SF in our Galactic Center + large kinematic overview in other nearby galaxy centers.

→ Relationship between gas flows, SF, and AGN activity over nearby galaxies, with resolved kinematics.

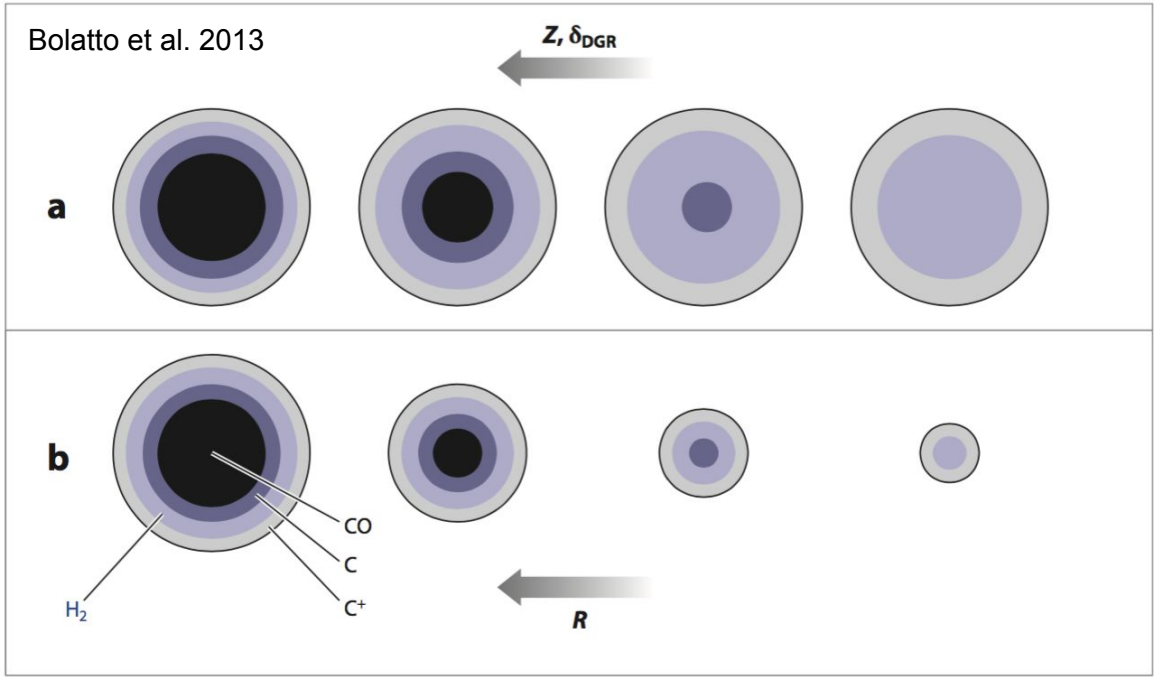
*High spatial resolution in dust continuum over a variety of molecular line transitions.*




holz &
sen 2015



How does the **C+/C/CO transition** change in molecular gas under different environmental conditions (especially low metallicity) and at different stages of the evolution of a molecular cloud?



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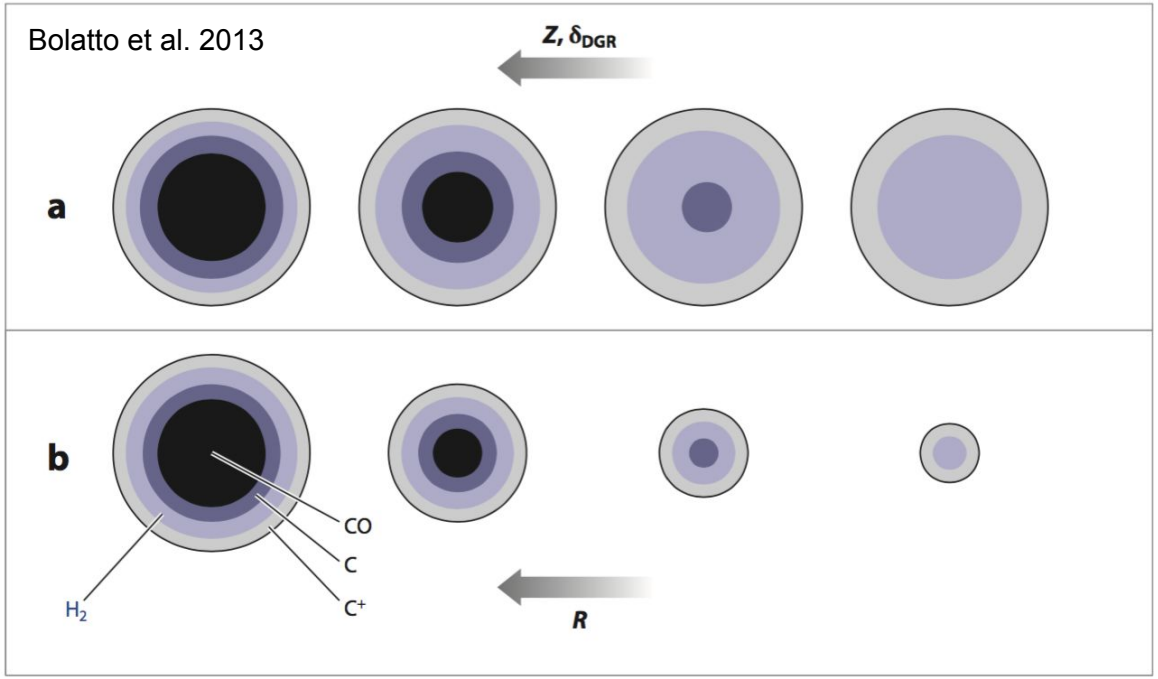
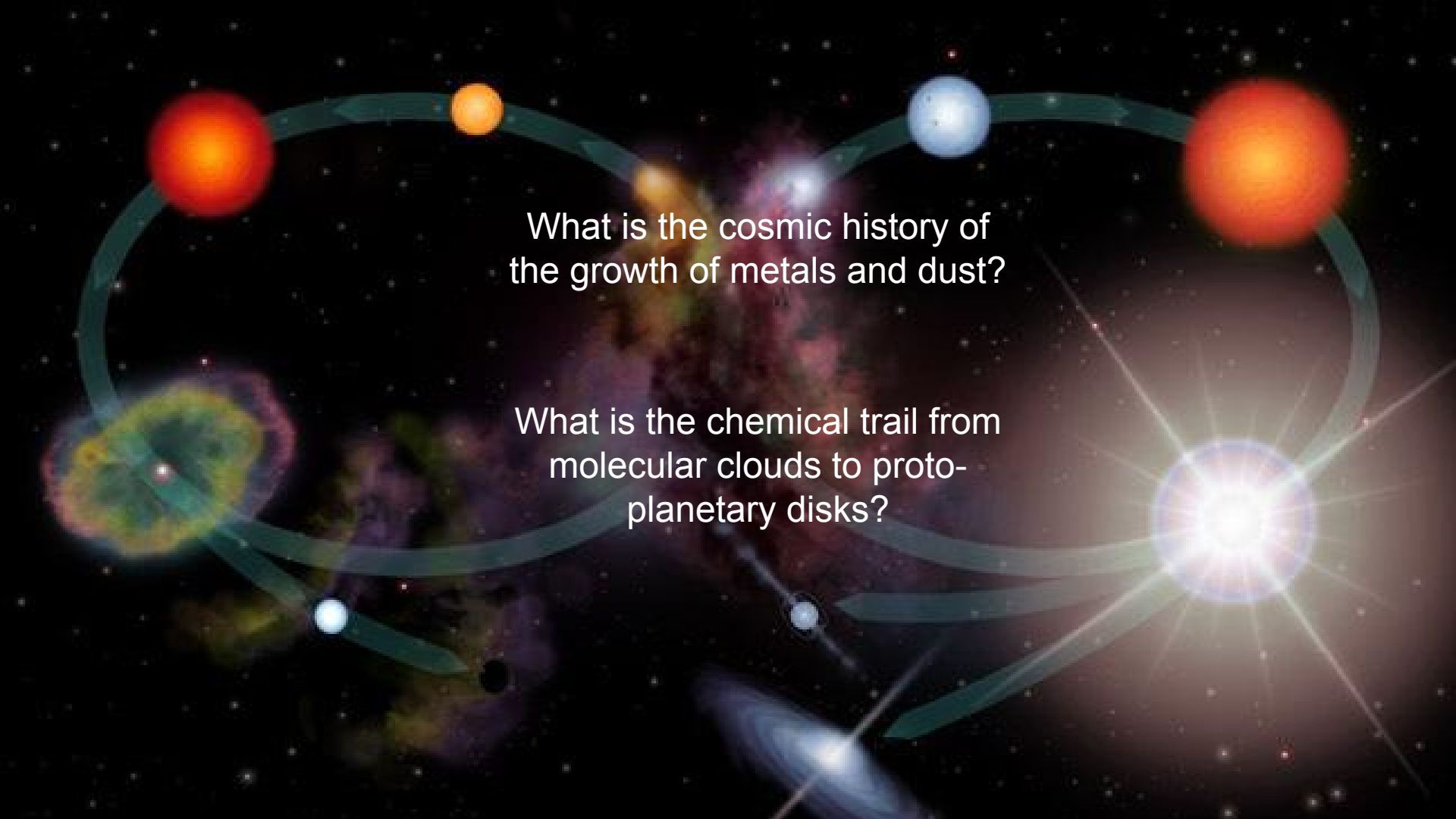
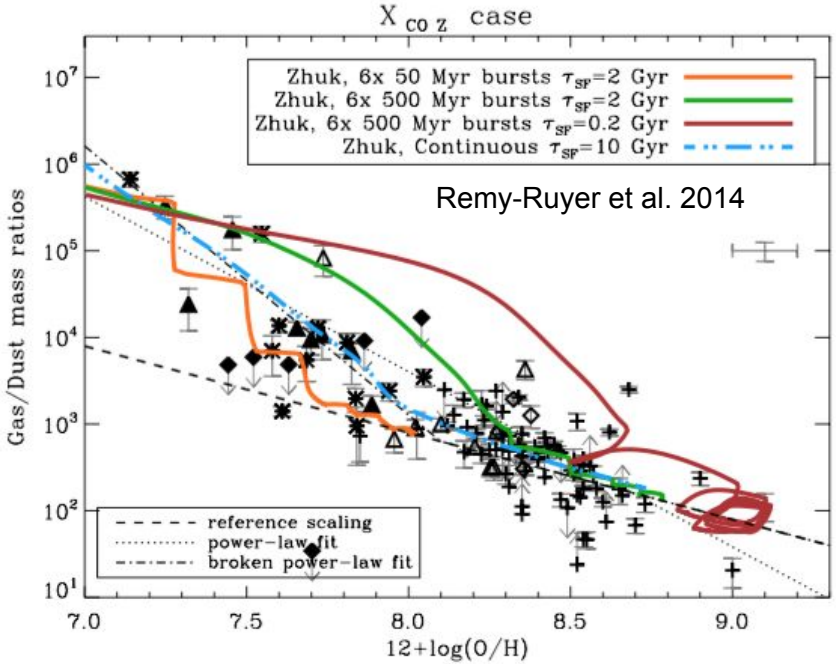



→ km/s resolution spectroscopy of [CII], [CI], other far-IR lines in nearby galaxies, comparison to CO from ALMA, HI from SKA
→ spectral mapping of far-IR lines in nearby galaxies
*Spectroscopy - mapping, velocity resolution in nearby galaxies.*


What is the cosmic history of the growth of metals and dust?
What is the chemical trail from molecular clouds to proto-planetary disks?

What controls the **life cycle of interstellar dust**? What are the timescales for dust growth and destruction in the ISM? How do they depend on local and global galaxy properties (e.g. metallicity, Hubble type)? Where and how the coagulation process take place? What is the role of dust (re-)growth in the ISM? What sources of dust could produce large dust masses in high redshift galaxies?



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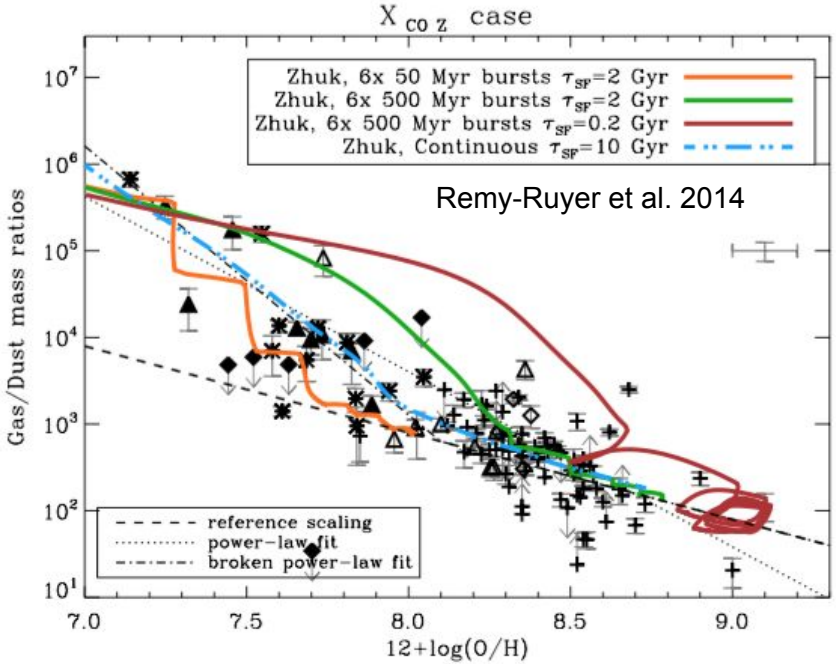
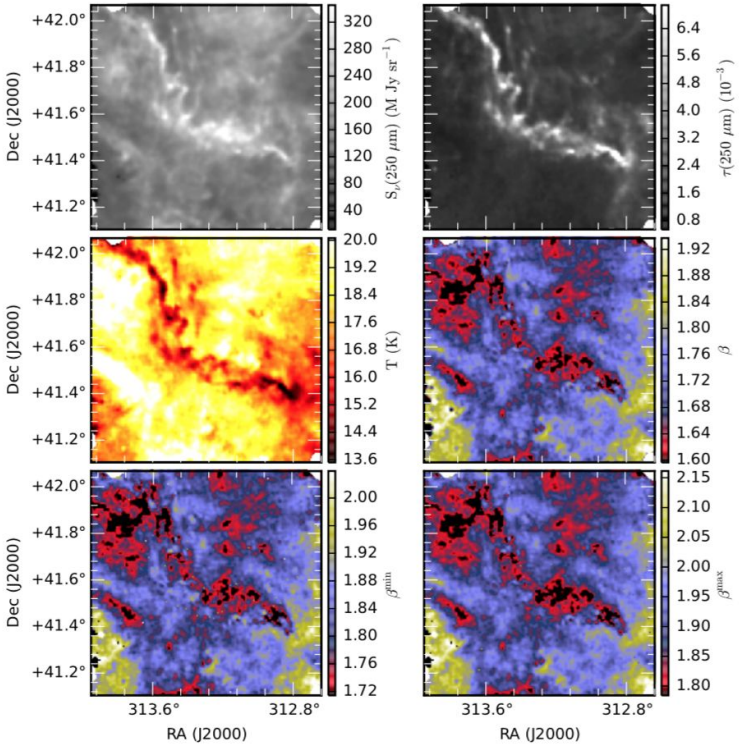



→ Deep photometric mapping of low metallicity galaxies, outskirts of spirals
→ Cloud scale far-IR mapping to track D/G as a function of ISM phase
→ Resolved dust maps in a large sample of nearby galaxies
*Sensitive mapping of regions with low dust surface density, large galaxy samples, high angular resolution imaging.*

What is the nature and abundance of the large grains in the ISM?  How does this grain population connect with the pre-planetesimal grains that are present in young stellar systems?  Does beta (dust emissivity spectral index) depend on wavelength?

Juvela et al. 2015



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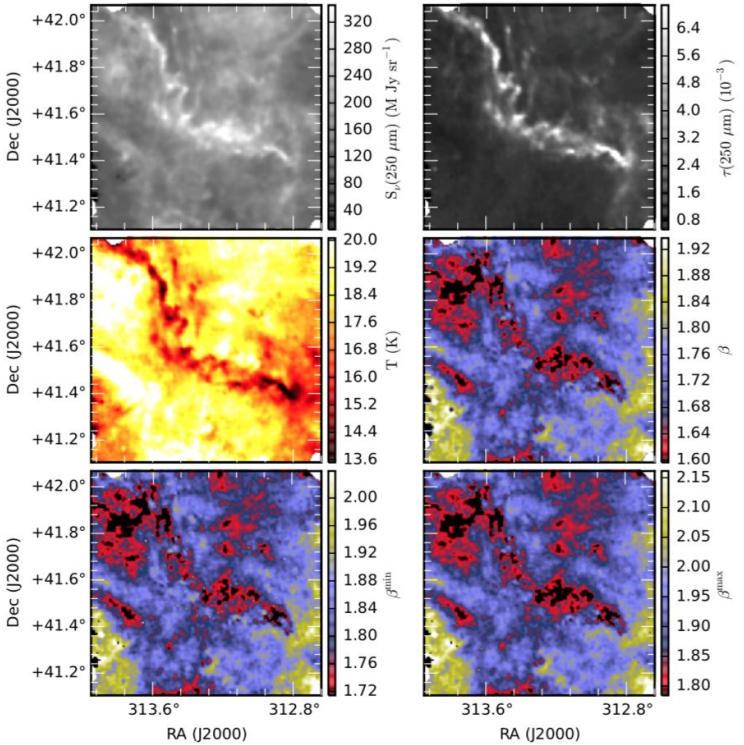



→ Multi-wavelength characterization of dust spectral indices is crucial for understanding grain growth and properties.

*Spectral mapping at far-IR/sub-mm wavelengths, high sensitivity, resolving structures where grain growth happens.*

How do complex molecules form and where do they form? What are the physical and chemical processes responsible for the creation (and destruction) of pre-biotic molecules? How prevalent are prebiotic molecules in interstellar clouds?

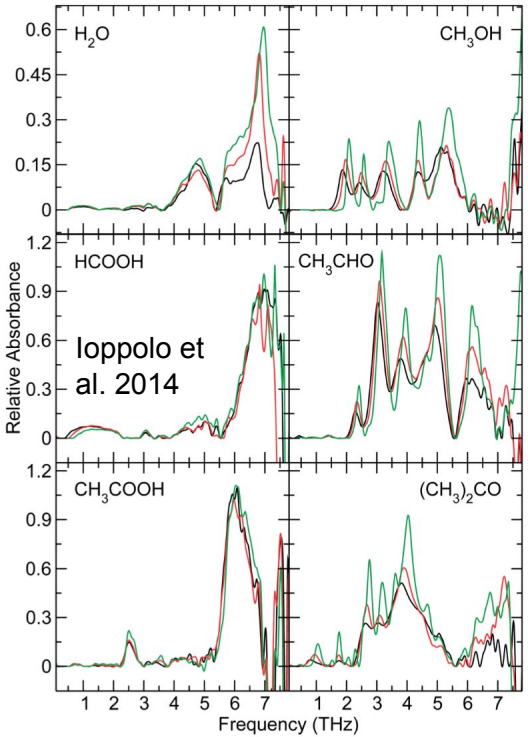
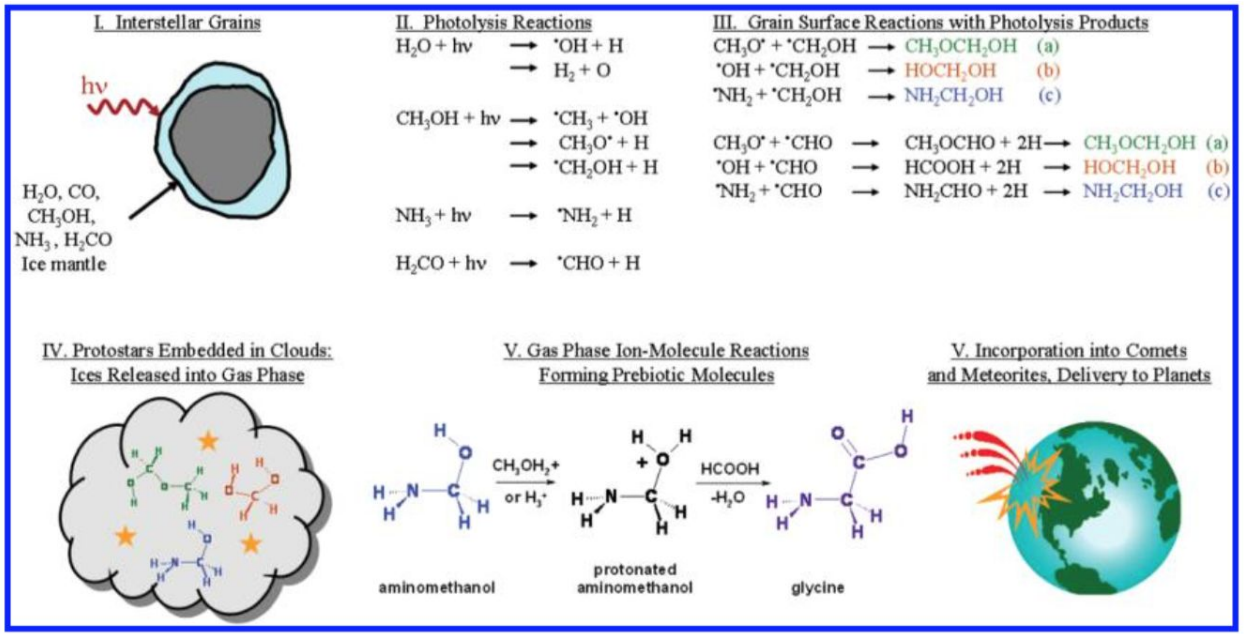



Fig. 6 THz spectra of crystalline ices at different temperatures: (black curves) 100 K; (red curves) 75 K; and (green curves) 10 K. The black curve of water ice is acquired at 140 K.




Garrod & Widicus Weaver 2013

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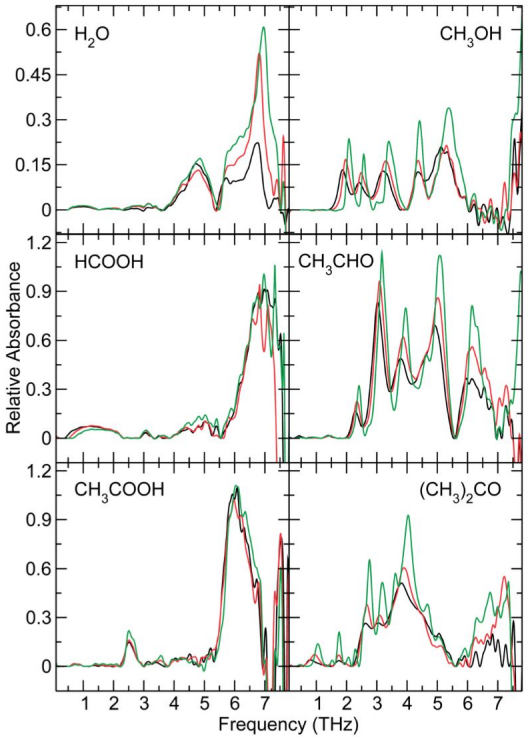
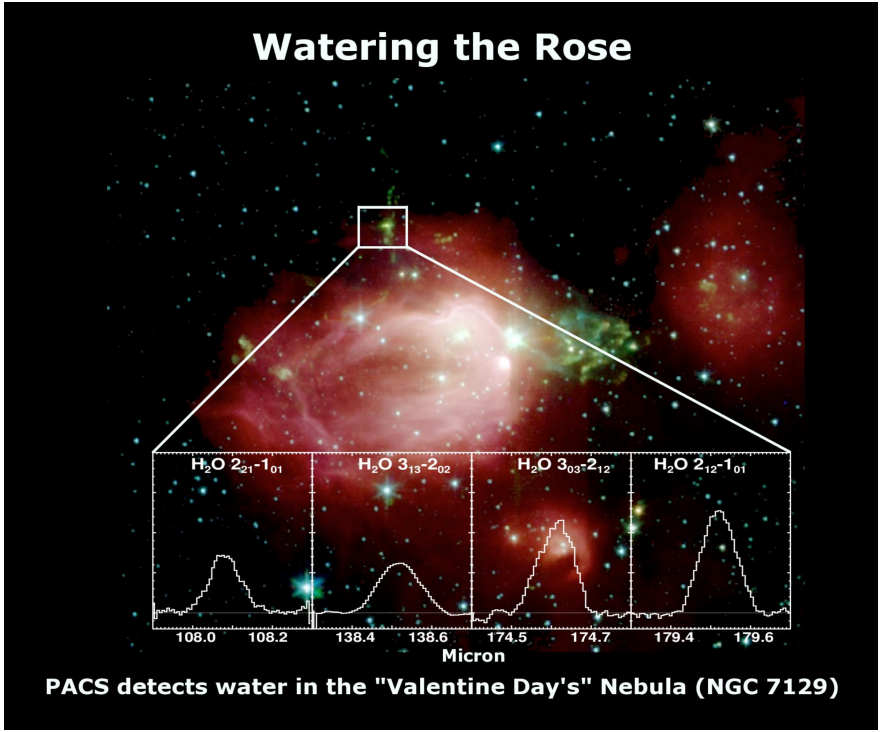



Fig. 6 THz spectra of crystalline ices at different temperatures: (black curves) 100 K; (red curves) 75 K; and (green curves) 10 K. The black curve of water ice is acquired at 140 K.

→ THz spectroscopy of ices
→ Spectral mapping of complex molecules in nearby star forming regions
*Spectroscopy, spectral mapping.*

What is the path of H2O from the interstellar medium to planets? What can we learn about deuterium chemistry in interstellar and circumstellar environments, and how does that inform our understanding of D/H in the solar system and the development of Earth's oceans?



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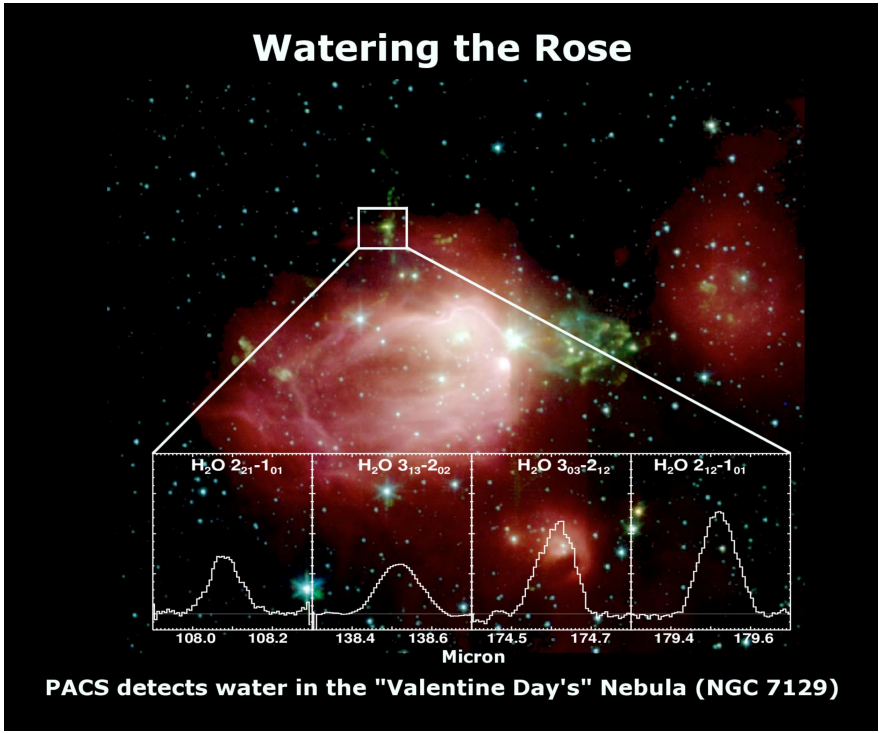

PACS detects water in the "Valentine Day's" Nebula (NGC 7129)

→ Observations of various $H_2{}^{16}O$ transitions at high spectral (and spatial) resolution.

→ Other gas-phase molecules also of interest.

→ Spectroscopy of water ice features to understand the chemistry (gas-phase vs. solid).

→

*$H_2O$ lines cannot be observed from balloons or SOFIA because of atmospheric absorption, far-IR from space is the only way to get at lines from cold $H_2O$.*

# Summary

- Identified several key areas for Far-IR Surveyor science
- Great progress and participation in defining these on short timescale
- Next stage will involve more detailed exploration of these areas
  - Which are uniquely suited to Far-IR Surveyor
  - Deeper look at what the frontier will be in 2030’s
  - Expert input on the areas we’ve defined (more theory, lab/experiment input)